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ORTHOPEDIC CAST DESIGN AND SIMULATION: INNOVATIONS FOR IMPROVED PATIENT CARE

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ABSTRACT

Some problems that often happen with clay casts are limited joint movement, muscle loss, and lower blood flow. There is a higher chance of systemic problems like clotting, local allergic reactions, skin trauma, compartment syndrome, and heat injuries. Plaster casts can cause skin sores from the pressure on the skin, skin infections, rashes, and stiffness in the joints over time. To get around these problems, many methods combining reverse engineering (RE) and additive manufacturing (AM) have been tested and shown to be effective in healing orthopedic casts problems, which are common fractures. Finite element analysis may be used to forecast the mechanical characteristics of devices such as orthopedic casts. In this study, we will use finite element analysis to examine the orthopedic cast designs' mechanical properties. Acrylonitrile butadiene styrene (ABS) was chosen as the material for this investigation because ABS is a recyclable material. A reduction in safety factor is observed as the weight imparted to the model increases. The utmost recommended burden at loading position 1 is 50 pounds of force. According to the findings derived from the simulations, the application of a 50-pound force burden will yield a safety factor of three. 10 pounds is the utmost weight that is recommended for loading position 2. This is based on the findings of the modeling, which suggest that the 10 lbf loading will generate a safety factor of 3.3. The maximum burden capacity that is advised for loading position 3 is 13 lbf. The deduction of this conclusion is supported by the simulation outcomes, which demonstrate that a 13-pound force application yields a safety factor of 3.01. 220 lbf is the utmost recommended force for loading position 4. Because the 220 lbf loading will produce a safety factor of 3.0, this is the case.

Keywords.: orthopedic oasts, finite element analysis, ABS, reverse engineering.

1. INTRODUCTION

One of the most prevalent orthopedic conditions is a fracture, and 2.4% of individuals will have one or more fractures throughout their lives on average [1]. Traumatic fracture is one of the most prevalent orthopedic issues that need medical and physical treatment. The shattered bone is decreased, and numerous methods are used to immobilize it [2]. Over 40% of all fractures in children occur in the forearm, and 7% of all pediatric trips to the emergency room include both the forearm and the wrist. Additionally, 20% of all pediatric visits are related to fractures in the forearm [3][4]. Distal forearm fractures are most prevalent in children aged five and above, with the highest incidence observed in males between the ages of 12 and 14 years and in girls between 10 and 12 years [5]. Although surgical options have been developed, most fractures are managed without surgery using a plaster or synthetic cast. Patients often describe casts as cumbersome, weighty, and painful, which hinders personal hygiene. This might lead to skin irritation, skin issues, or even temporary malfunction of the radial sensory nerve if administered incorrectly. Aside from being inconvenient, a significant drawback of a cast is the potential for subsequent fracture dislocation, which may happen in as many as 75% of patients [6].

Plaster casting, using gypsum plaster or plaster of Paris, has remained almost unchanged from its inception in the 10th century. The traditional casts have benefits such as simple manipulation, flexibility, and affordability. However, their drawbacks include being heavy, not breathable, not water-resistant, and not allowing direct observation of soft tissues, which may lead to potential skin responses and restrict their use. In the 1970s, the emergence of fiberglass casts offered a more robust and water-resistant option, however, they did not completely resolve the other drawbacks [7]. Common issues associated with plaster casts include restricted joint movement, muscle atrophy, and reduced blood flow. Systemic problems such as thromboembolism, local allergic reactions, skin trauma, compartment syndrome, and heat traumas provide a higher risk. Delayed local consequences of the plaster cast include plaster sores due to pressure on the skin, skin infection, dermatitis, and joint stiffness [8]. To address the above limitations, several methodologies using reverse engineering (RE) and additive manufacturing (AM) methods have been implemented and shown as viable options for treating hand-wrist-arm (HWA) pathologies, which are prevalent fractures. By using approaches starting with the acquisition of arm-wrist-hand district anatomy, it is feasible to produce a personalized orthosis with mechanical attributes, such as stiffness, comparable to those of standard casts [9]. Several additive manufacturing techniques have been used in engineering applications. SLA, FDM, DMLS, 3DP, SLM, PolyJet Technology, and EBM are several processes used [10].

An orthosis is a medical device used in orthopedics and traumatology to restrict joint motions after trauma, surgery, sprains, or for individuals with arthritis. Furthermore, an orthosis may help decrease joint stress and avoid skeletal deformities [11]. Fracture immobilization complications and the heavy burden of fracture management have led to the exploration of novel methods such as 3D-printed casts. These casts offer advantages over traditional immobilization methods, improving physiotherapy outcomes by increasing patient satisfaction, comfort, pain relief, exercise ability, and reducing skin irritation. Common fracture problems such as unstable or refractured bone, compartment syndrome, and pressure sores are rare with 3D-printed casts [2]. The 3D-printed casts provide advantages such as a tailored fit, breathability, reduced weight, waterproof properties, and the option to include an aperture over the incision to prevent pressure points. Furthermore, they might include an attractive and personalized aesthetic design. These elements may result in improved patient satisfaction and enhanced patient compliance [12]. A 3D-printed cast is a plastic casing that protects and immobilizes a fractured or broken limb in three dimensions. 3D printing allows for the precise production of patient-specific casts and splints using a combination of a 3D scanner, powerful 3D modeling software, and a fast prototyping machine [13].

Prior research has shown that finite element (FE) analysis in medicine aids surgeons in comprehending the overall biomechanical characteristics of damaged tissues and medical equipment [14,15]. The biomechanical characteristics of a cast-wrapped damaged forearm during therapy remain uncertain. FE modeling may forecast changes in stress distribution and fracture displacement over the whole range of motion for the computer-designed cast. Scant research has been conducted to comprehensively illustrate the biomechanical characteristics of a broken forearm bone with an orthopedic cast on a worldwide scale [16]. Finite element analysis (FEA) was employed to simulate the mechanical behavior of scaffolds and orthopedic casts, among other devices [17]. Finite element analysis may be used to forecast the mechanical characteristics of devices such as orthopedic casts, scaffolds, and hip prosthesis [18–20]. This work aims to analyze the mechanical characteristics of orthopedic cast designs by finite element analysis.

2. MATERIALS AND METHODS

2.1 Materials

Acrylonitrile butadiene styrene (ABS) was chosen as the material for this investigation because ABS is a recyclable material. Thermoplastic polymer like Acrylonitrile Butadiene Styrene (ABS) is often used in many industries, especially when seeking to combine impact resistance with an attractive aesthetic and eco-friendly design [21]. ABS consists of three monomers: acrylonitrile, butadiene, and styrene. The product is generated by altering a copolymer resin (styrene-acrylonitrile) with another copolymer (butadiene, acrylonitrile) [22]. The technical specification data of the material is shown in Table 1.

Table 1. Properties of ABS materials [23]

Properties	**Value**
Poisson ratio	0.38
Elastic modulus (kpsi)	224.88
Solid density (lb mass/in^3)	0.038
Yield strength (psi)	2900

2.2 Methods

There was a standard five-step procedure for the creation of orthopedic casts. Step one involves using a 3D scanner or other medical imaging equipment to collect image data that includes 3D spatial information about the limb. In phase 2, computer-aided design and reverse engineering tools are used to further create the orthopedic castings. The subsequent procedure involves creating a hand surface with the use of mesh mixer software, which also performs the thickening and air vent hole generation functions. The following phase involves creating components for the orthopedic casts for simple assembly. CAD software is used for designing the parts, and the final design stage includes simulation using Autodesk Inventor Professional 2020 software.

3. RESULTS AND DISCUSSION

The outcomes of the hand-arm scanning procedure using 3D Scan are provided as STL files. STL files are manipulated using mesh mixer software for streamlined processing. The goal of processing the STL file is to create a model that closely matches the 3D scan findings in terms of both form and size accuracy. The outcome of this procedure is a collection of geometries that form a model in the shape of a surface. To create a surface, use the Brush tool in Meshmixer, then refine it by using the Smooth Boundary function. Figure 1 illustrates the surface generation process. The produced surface is further smoothed, as seen in Figure 2.

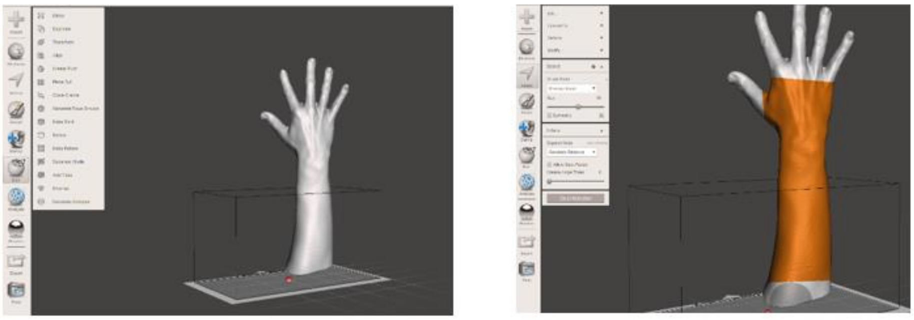


Figure 1. The surface generation process.

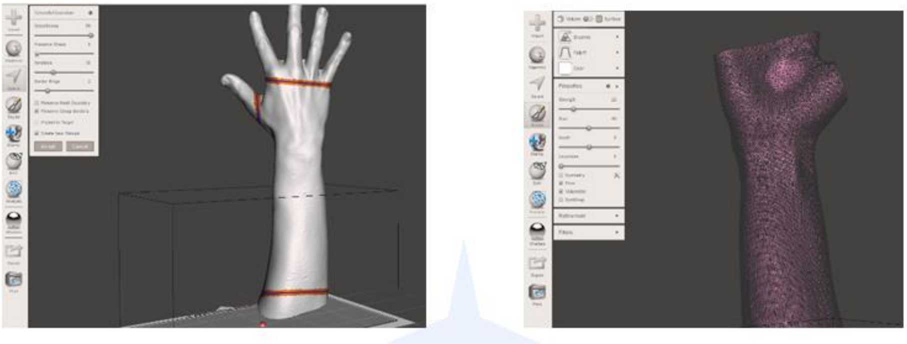
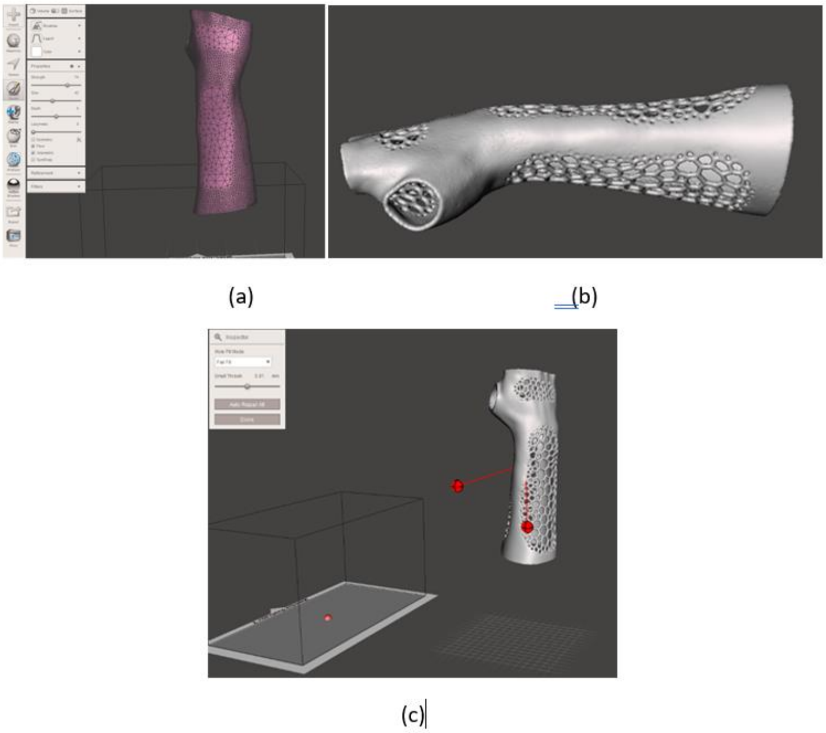


Figure 2. Surface smoothing process.

The method of creating holes starts with mesh reduction. The setting is adjusted to 85% to increase the width of the mesh line. The goal is to ensure that the processor load is light during data processing to minimize processing time. After lowering the amount of meshes using the mesh reduction option. The subsequent step involves perforating the mesh. The hole is created using the sculpt option in the mesh mixer software. This characteristic determines which components will be included in the ventilation hole and which will stay solid. The sculpt feature consists of two parts: refine and reduce. The refine function is used to modify or enhance the structure of the mesh component, while reduce is employed to decrease the structure of the mesh component. The hole design or location is located on the top and bottom surfaces of the model. Figure 3 displays the outcomes of the hole-creating operation.



(a) (b)

(c)

Figure 3. The hole-making method (a) mesh reduction process, (b) hole design process, and (c) process for repairing a hole

The subsequent action involves dividing the orthopedic cast model into two halves. This is designed to be simple during the installation procedure in the patient's hand. The orthopedic cast is divided into two sections: the top and bottom. The cut groove is created in a puzzle design on one side to serve as a binder, preventing the pattern from separating during usage. The puzzle's dimensions create an angle of 40-70 degrees on the left side and 100-120 degrees on the right side when put lengthwise. The line is then thickened to 0.3 mm along the surface axis. The left surface direction intersects the Z axis from the outside left side towards the interior of the arm cast, while the right surface direction intersects horizontally from the outer right side towards the inside. Next, create holes for bolts to secure and provide safety for both halves of the orthopedic cast simultaneously. Figure 4 displays the design process of the zigzag and locking components.

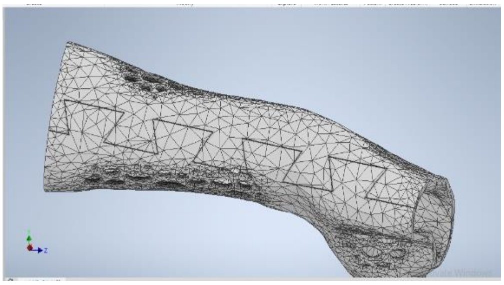


Figure 4. Zig-zag cutout design

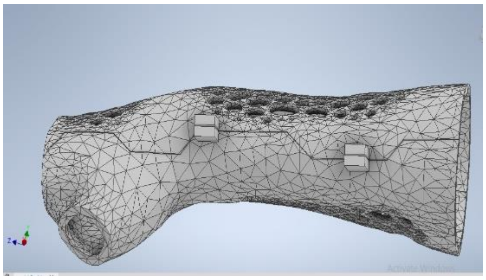


Figure 5. Locking design

Autodesk Inventor software was used to conduct static analysis. Inventor is used for testing because of its capability to test complex meshes with several architectural structures. Three tests are used in this static analysis procedure, with the fixed position/constraint located at the bottom of the model. The simulation was conducted using 4 loading locations. The load is positioned at the top of the model at position 1. The load is positioned on the back of the palm in position 2. Position 3 places the weight on the palm, whereas position 4 distributes the stress throughout all regions of the model. Figure 6 displays the loading location in all positions.

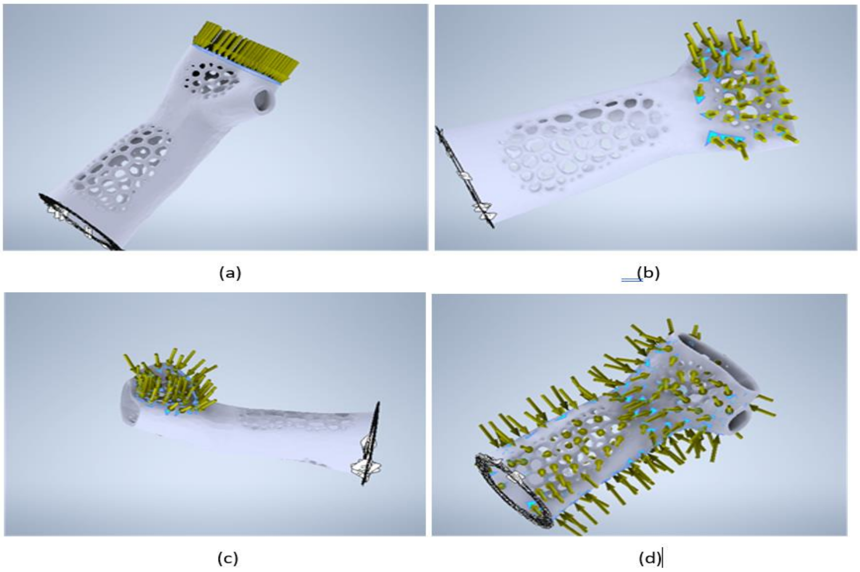


Figure 6. Loading position during the simulation process (a) top of the model, (b) back of the palm, (c) palm of the hand, and (d) all surface model.

Simulations were conducted at each step based on the loading position using 5 distinct kinds of loading to determine the model's maximum capacity under various loading conditions. Table 2 displays the five forms of loading.

Table 2. The amount of loading for each simulation

Loading Position	F1 (Lbf)	F2 (Lbf)	F3 (Lbf)	F4 (Lbf)	F5 (Lbf)
1	50	120	140	160	170
2	10	20	30	40	50
3	10	13	15	20	30
4	100	140	220	250	300

The final result expected from this research is the safety factor value of each simulation due to the effect of loading. The simulation results in the form of safety factors are shown in Figure 7.

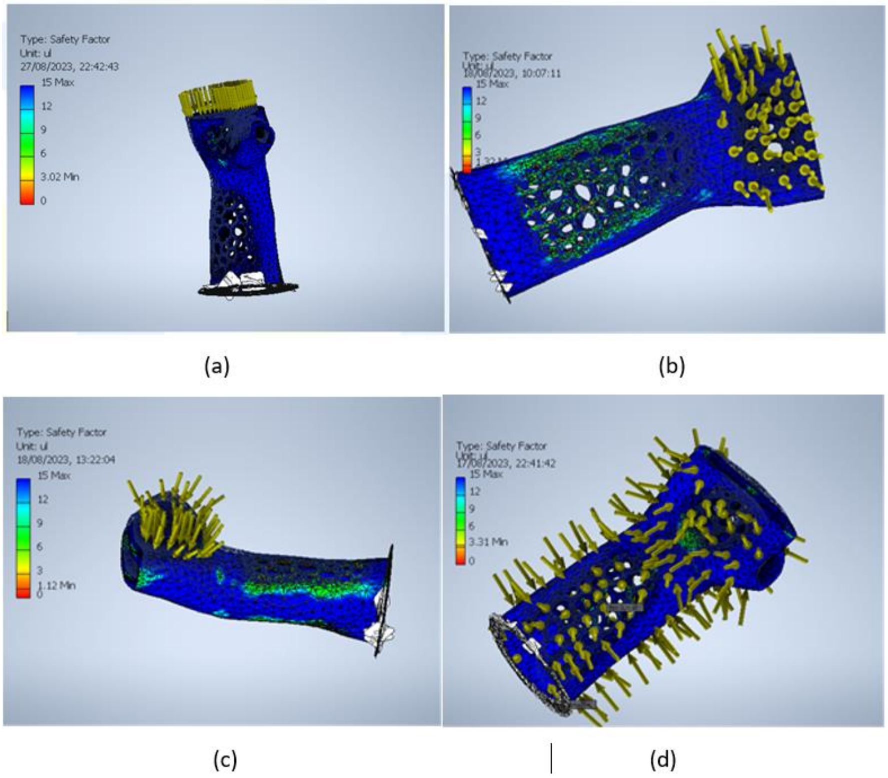


Figure 7. The safety factor of the simulation results: (a) loading position 1, (b) loading position 2, (c) loading position 3, and (d) loading position (4).

The ratio of the actual strength to the required strength is called the safety factor. The SF value has a range (1 < SOF < 10), if the FOS value is less than 1(FOS < 1), then the quality of the product is said to be unsafe to make and needs improvement, and vice versa if the SOF value is more than 1(SOF> 1) then the product is said to be safe and of good quality. The safety of factor value of ABS material with a yield strength value of 2900 psi using Autodesk Inventor 2020 software. In the design of the orthopedic cast design, the maximum FOS standard applied is a maximum of 3. Figures 8 to Figure 11 illustrate the size of the safety factor that was calculated based on the simulation results with varying loading positions and loading magnitudes.

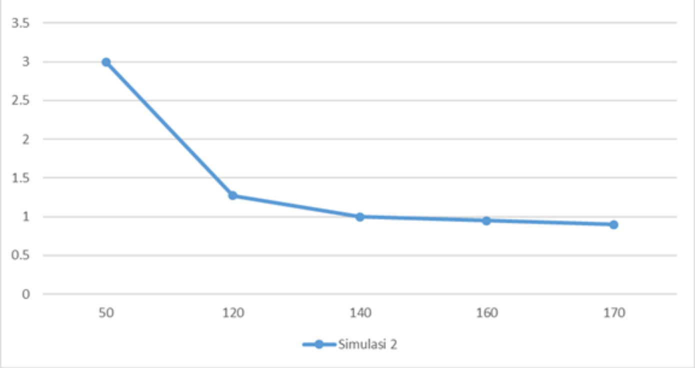


Figure 8. The safety factor derived from simulation outcomes under varying loads at loading position 1.

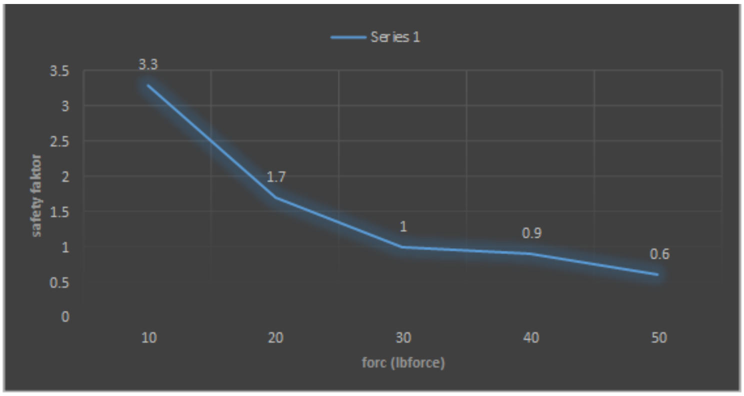


Figure 8. The safety factor derived from simulation outcomes under varying loads at loading position 2.

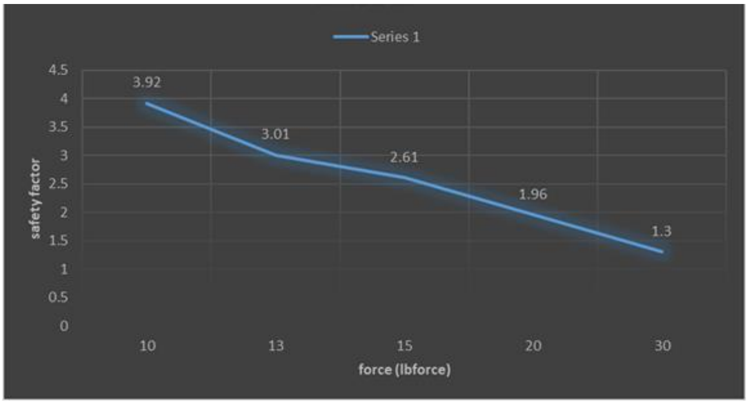


Figure 10. The safety factor derived from simulation outcomes under varying loads at loading position 3.

According to Figure 8, when the weight applied to the model increases, the safety factor decreases. At loading position 1, the maximum suggested load is 50 pounds-force. These results are based on simulations and indicate that a 50 pounds-force load will result in a safety factor of 3. Figure 9 illustrates how the safety factor will drop when the model is subjected to greater loads. The maximum weight that is advised for loading position 2 is 10 lbf. This is predicated on the modeling results, which indicate that a safety factor of 3.3 will be produced by the 10 lbf loading.

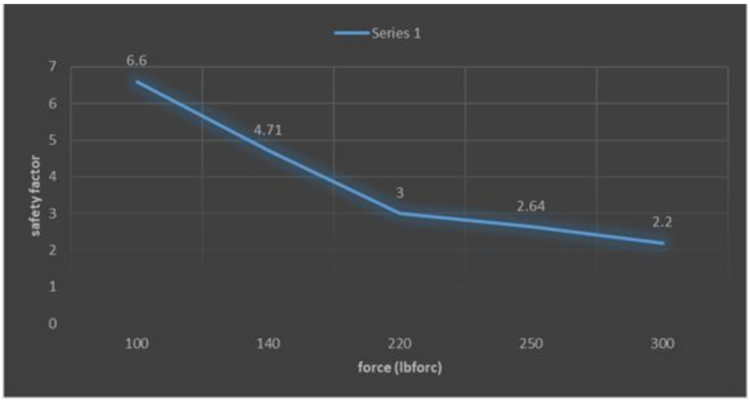


Figure 11. The safety factor derived from simulation outcomes under varying loads at loading position 4.

As illustrated in Figure 10, as the burden applied to the model increases, the safety factor correspondingly diminishes. 13 lbf is the utmost load capacity recommended for loading position 3. This conclusion is drawn from the simulation results, which indicate that a safety factor of 3.01 can be obtained with a 13-pound force loading. Figure 11 shows that the safety factor decreases as the model's load increases. The maximum suggested load in loading position 4 is 220 lbf. This is due to the fact that the 220 lbf loading will result in a safety factor of 3.0, as shown in the simulation results.

4. CONCLUSIONS

Common issues with clay casts include restricted joint mobility, muscular atrophy, and reduced blood circulation. Systemic issues such as clotting, local allergic responses, skin damage, compartment syndrome, and heat injuries are more likely to occur. Plaster casts may lead to skin ulcers due to pressure, skin infections, rashes, and joint stiffness with prolonged usage. Various techniques that integrate reverse engineering (RE) with additive manufacturing (AM) have been experimented with and shown to be successful in addressing issues with orthopedic casts, often used for treating fractures. Finite element analysis can predict the mechanical properties of devices like orthopedic casts. As the applied weight on the model grows, the safety factor drops. The recommended maximum load at loading position 1 is 50 pounds-force. The findings are derived from simulations and show that a 50 pounds-force load will provide a safety factor of 3. The recommended maximum weight for loading position 2 is 10 pounds-force (lbf). The modeling findings suggest that a safety factor of 3.3 will be achieved with a 10 lbf weight. The maximum load capacity advised for loading position 3 is 13 pounds-force. The simulation findings show that a safety factor of 3.01 may be achieved with a 13-pound force loading. The maximum recommended load for loading position 4 is 220 pounds-force. The 220 lbf payload will lead to a safety factor of 3.0.

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